Violations of local friendliness with quantum computers

William J. Zeng[1,2], Farrokh Labib[1], Vincent Russo[1]

[1]Unitary Fund, [2]Quantonation

Local friendliness

Absoluteness of Observed Events (AOE): Every observed event happens for all observers.

Local Agency (LA): Events are uncorrelated with other events outside its future light cone.

Local Friendliness (LF): The conjunction of AOE and LA.

In this work, we:

- Propose how quantum computers can be used to build more meaningful tests of LF.
- Use quantum computers to give experimental evidence (with loopholes) of LF violations.

Wigner's friend

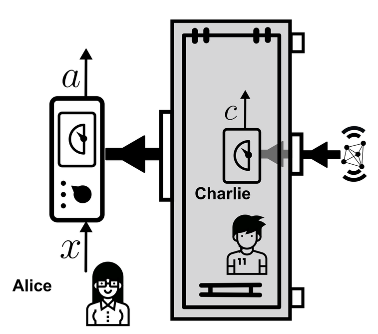

Figure 1: System is sent to Charlie's sealed lab. Alice has different measurement settings labeled by x to observe the sealed lab that contains her friend Charlie and his measurement outcome c. Alice's measurement outcome is labeled a.

Branch factor for observerness

The *branch factor* quantifies the "observerness" of a friend and measures how macroscopically separated the friend is after interacting with a quantum system.

Interference complexity: $C_I(|\psi_0\rangle, |\psi_1\rangle, \delta)$ is equal to $\min_U(C(U))$ such that

$$\frac{|\langle\psi_1| U |\psi_0\rangle + \langle\psi_0| U |\psi_1\rangle|}{2} \geq \delta.$$

Distinguishability complexity: $C_D(|\psi_0\rangle, |\psi_1\rangle, \delta)$ is equal to $\min_U(C(U))$ such that

$$\frac{|\langle\psi_0| U |\psi_0\rangle - \langle\psi_1| U |\psi_1\rangle|}{2} \geq \delta.$$

Branch factor:

$$B(|\psi_0\rangle, |\psi_1\rangle, \delta) = C_I(|\psi_0\rangle, |\psi_1\rangle, \delta) - C_D(|\psi_0\rangle, |\psi_1\rangle, \delta).$$

Branch factor is good when

$$C_I(|\psi_0\rangle, |\psi_1\rangle, \delta) \gg C_D(|\psi_0\rangle, |\psi_1\rangle, \delta)$$

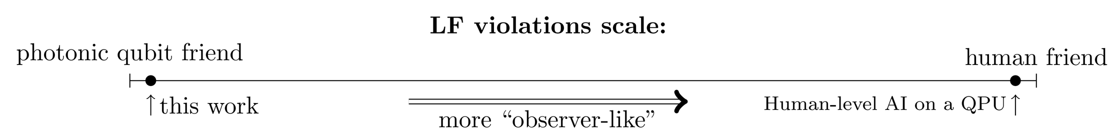

Figure 2: A program designed to test LF violations on a progressively larger scale increases the viability of the observers used as friends.

Local friendliness violations on quantum computers

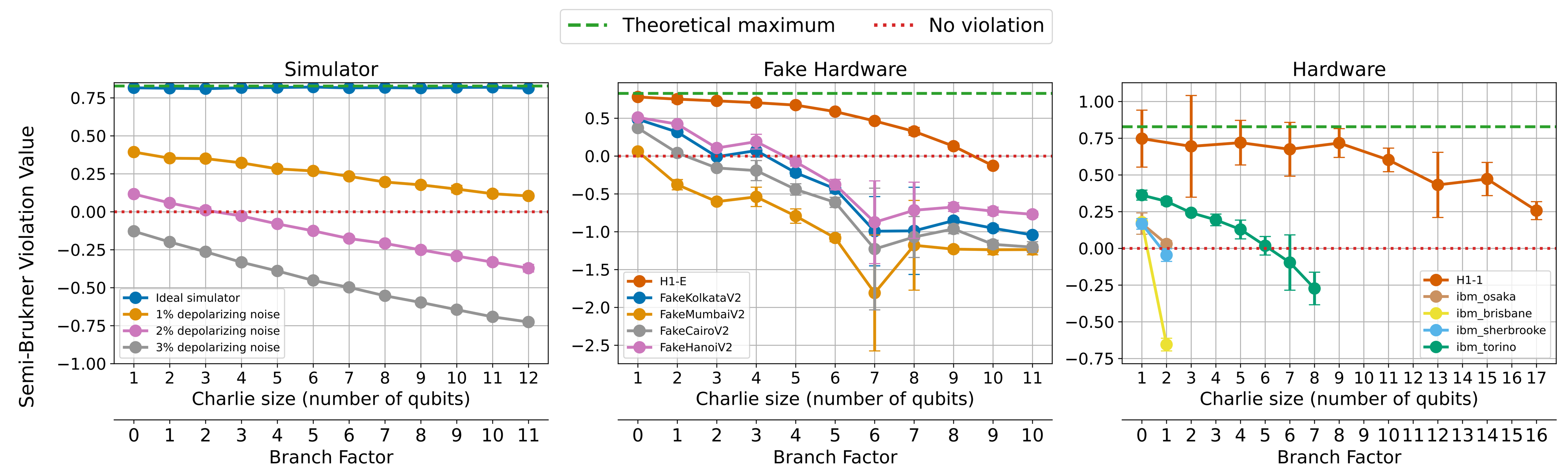

Figure 3: **A comparison between simulator, fake hardware, and hardware for majority vote EWFS.** First panel shows how increasing the depolarizing noise reduces maximum friend size for which a violation occurs. Second-panel plots over the `FakeTorino`, `FakeOsaka`, and `FakeQuebec` fake IBM noise models as well as the `H1-E`, the emulator for the Quantinuum H1 ion trap quantum computer. Third panel plots over the `ibm_osaka`, `ibm_sherbrooke`, and `ibm_torino` IBM hardware devices. Note that the only IBM hardware device to obtain violations beyond branch factor 0 is `ibm_torino`, showing a violation at branch factor 4. Bottom x-axis ranges over number of qubits in the quantum system size of Charlie, while top x-axis shows corresponding branch factor. All IBM data points are run with 10000 shots over 10 trials.

Extended Wigner's friend scenario

Extended Wigner's friend scenarios (EWFS) comprise parallel instances of the original Wigner's friend thought experiment.

EWFS: Incorporate Wigner's friend into a Bell experiment. EWFS shows that textbook quantum mechanics violates LF.

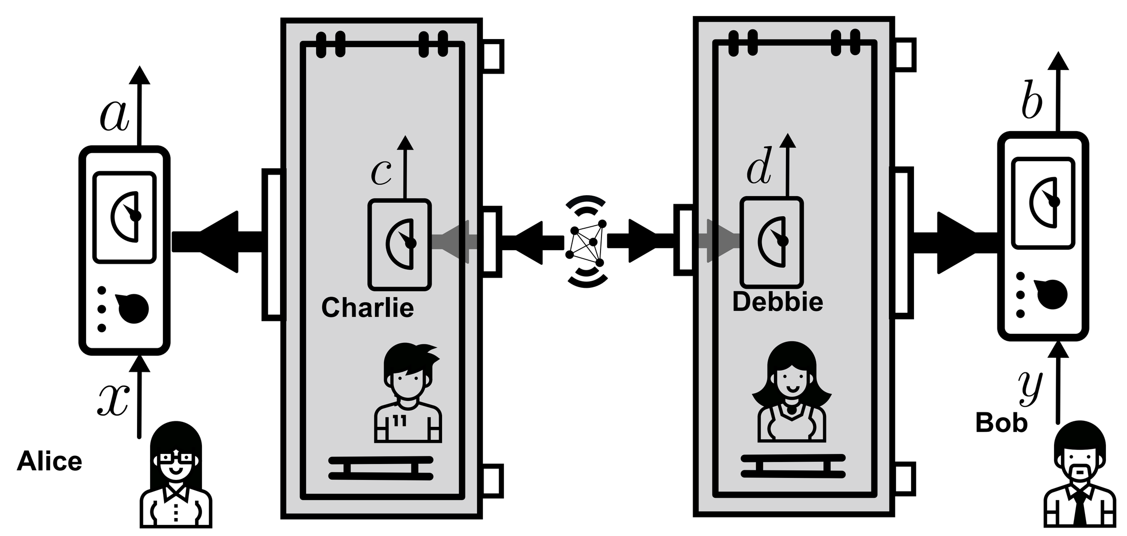

Figure 4: **Extended Wigner's friend scenario (EWFS).** A system is split and sent into two sealed labs. Alice has different measurement settings labeled by x to observe the sealed lab that contains her friend Charlie and Charlie's measurement outcome c. Similarly, Bob has measurement settings labeled by y for the sealed lab containing Debbie and her measurement outcome d. Alice's measurement outcome has the value labeled a, and Bob's has the value labeled b.

Semi-Brukner inequality: One of the LF inequalities we consider and show violations for:

$$-\langle A_1 B_2\rangle + \langle A_1 B_3\rangle - \langle A_3 B_2\rangle - \langle A_3 B_3\rangle - 2 \leq 0.$$

Measurement: Two ways for Alice and Bob to measure the quantum system.

Peek: Open lab and "peek" at classical measurement outcome recorded by friend in the lab.

Reverse: Reverse measurement that the friends performed.

Call-to-action: We introduce this program as a fundamental science application for near-term and developing quantum technology.

Quantum circuit for EWFS

Approach: EWFS can be encoded in a quantum circuit and run on existing quantum hardware for progressively larger quantum system sizes.

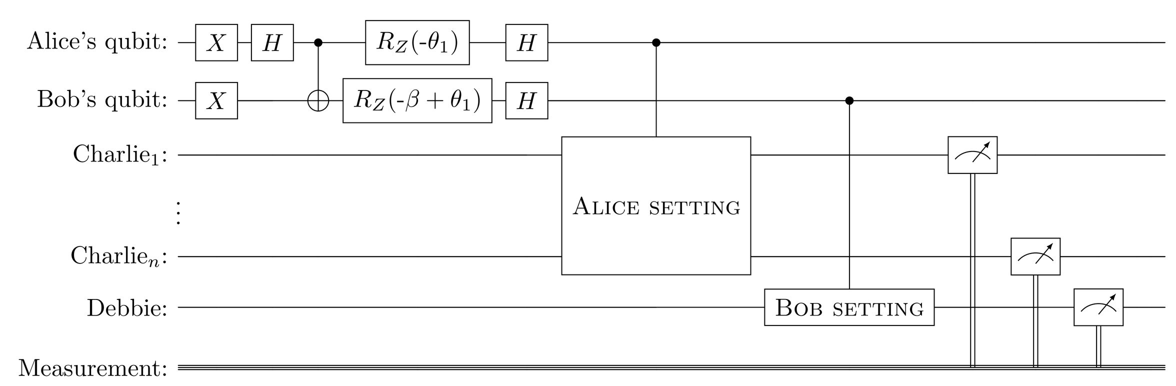

Figure 5: **Circuit depiction of the EWFS.** Alice and Bob begin by preparing a bipartite state. Alice then performs her measurement setting on Charlie's qubit(s); likewise, Bob performs his measurement on Debbie's (single) qubit. The settings performed by Alice and Bob are either PEEK, REVERSE-1, or REVERSE-2. Finally, the system qubits of Charlie and Debbie are measured.

Local friendliness polytope

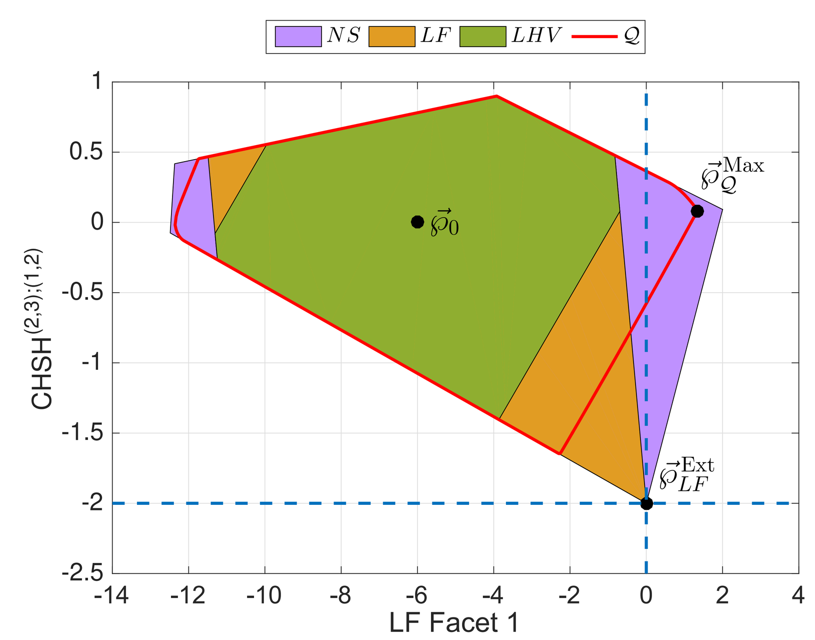

Figure 6: **A 2D slice of the LF polytope.** The orange area represents the space of LF correlations (which can be outside of the quantum boundary represented by the red line).

Software

We implemented our experiments in Python 3.12 using Qiskit v.1.0.2. Supporting code is available at https://github.com/unitaryfund/research/.

Acknowledgements

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